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Ice & Fire: Missions to the Most Difficult Solar System Destinations... on a Budget

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Abstract

Three radii from the surface of the Sun...more natural radiation around Jupiter than would be encountered immediately following a nuclear war...to the farthest planet and beyond...these challenges are faced by the three "Ice & Fire" missions: Solar Probe, Europa Orbiter, and Pluto-Kuiper Express. These three missions will be beneficiaries of the X2000 and related advanced technology development programs. Technology developments now in progress make these missions achievable at costs recently thought adequate only for missions of relatively short durations to "nearby" destinations.

The next mission to Europa after *Galileo* will determine whether a global subsurface liquid water ocean is currently present, and will identify locations where the ocean, if it exists, may be most accessible to future missions. Pluto-Kuiper Express will complete the reconnaissance of the known planets in our Solar System with geological, compositional, and atmospheric mapping of Pluto and Charon while Pluto remains relatively near the Sun during its 248 year orbit. An extended mission to a Kuiper Disk object may be possible, depending on remaining sciencecraft resources. Using a unique combination of Sun shield/high gain antenna and quadrature encounter geometry, Solar Probe will deeply penetrate our nearest star's atmosphere to make local measurements of the birth of solar wind, and to remotely image features as small as 60 kilometers across on the Sun's surface.

Avionics technology, leading to integration of functions among a set of multichip modules with standard interfaces, will enable lower

production costs, lower power and mass, and the ability to package with modest shielding to enable survival in orbit around Europa inside Jupiter's intense radiation belts. The same avionics and software can be utilized on the other Ice & Fire missions. Each mission is characterized by a long cruise to its destination, interrupted by planetary flybys. The flight systems will represent a unique early integration of science "payload" and "spacecraft," becoming a more integrated "sciencecraft." To reduce operations and tracking costs, sciencecraft will be more autonomous. They will self-monitor and self-command, while sending a continuous beacon alerting ground receivers to general sciencecraft health and any need for immediate attention. Where solar power proves impractical for achieving mission goals, an advanced radioisotope power source may be utilized with a much smaller amount of fuel than on prior missions.

The three missions described are to begin the Outer Planets/Solar Probe exploration program, as first proposed in the FY1998 Federal Budget. Sciencecraft, launch systems and mission operations must all fit within a single program, encouraging system- and program-wide tradeoffs to minimize costs. Some of the system and technological solutions utilized by these missions may find application in a variety of other science-driven missions.

PROGRAM CONTENT AND APPROACH

The first three Outer Planets/Solar Probe (OP/SP) missions are being developed and implemented as a single project. Presently

(See Fig. 0)

→ the first mission is planned to be Europa Orbiter, launching in 2003, followed by Pluto-Kuiper Express launching in 2004, and Solar Probe in early 2007. An option will be maintained into 2000 to reverse the order of the first two launches, in the event that the unique challenges of the Europa Orbiter mission require an extra year to solve.

[hyplan?] Though ultimately targeted for three very different destinations, all three missions will utilize Jupiter flybys to reduce required launch vehicle size. The three sciencecraft will share nearly all their avionics in common, along with some telecommunications and propulsion components. Core software will be common, including that controlling generic sciencecraft functions, and the three missions will be operated during their long cruise periods by a common team. These functions of interplanetary missions typically add up to a large fraction of a mission's total cost.

Most of the common components of these missions are being developed and qualified by the Advanced Deep Space System Development Program's (ADSSDP) X2000 First Delivery Project.¹ The three OP/SP missions represent three of the five primary customers for this First Delivery Project; the other two customers are the New Millennium Deep Space - 4/Champion comet mission, and Mars Sample Return. For those missions which may require a non-solar primary power source, the Department of Energy is developing an Advanced Radioisotope Power Source (ARPS) as part of the ADSSDP.^{2,3}

With the ability to utilize the non-recurring cost investment represented by the ADSSDP developments, and the sharing of some further non-recurring costs across the three flight systems, the equivalent "Phase C/D" cost for each of the three OP/SP missions without launch vehicle is estimated to be less than the benchmark Mars Pathfinder cost of FY97\$190M.

Some aspects of the three missions are clearly unique: most notably the science and instrumentation, trajectories, propulsion

and radiation shielding for the Europa Orbiter, and thermal shielding for Solar Probe. Launch systems will also differ, depending on availability and performance. In spite of these differences, a single team will complete preliminary design of the three flight systems using largely X2000 hardware and software. A single trajectory/mission design team will develop all three missions, as will a single launch system team. As each mission in turn enters detailed design, a dedicated mission implementation team will be formed, with the leader for each such team reporting to the project manager. There will be sharing of some individuals across more than one mission team, both to enhance communication of common issues, and to smooth work loading. Work has begun to assist NASA in preparing a science investigation Announcement of Opportunity for the three missions. Members of the selected science investigation teams will become part of the flight system and mission/trajectory design teams.⁴

SCIENCE OBJECTIVES DRIVING THE MISSIONS

The science objectives for the Outer Planets/Solar Probe Project were developed for each mission through close interaction with the science community. A Science Definition Team, appointed by NASA Headquarters, was formed for each mission. The teams identified the most important scientific questions to be addressed by each mission and formed a set of primary and secondary science objectives. The primary, or "Category 1A" objectives are the "must do" science that justify the mission.⁵ The secondary objectives, if fulfilled, enhance the science return of the mission but are not allowed to drive the design or cost of the mission. A "strawman" science payload and measurement set were also developed for each mission to show the feasibility of fulfilling the primary science objectives. For brevity, only the primary objectives for each mission are discussed here.

EUROPA ORBITER SCIENCE

The primary objectives of the Europa Orbiter Mission are: 1) determine the presence or absence of a subsurface liquid ocean; 2) characterize the 3D distribution of subsurface liquid water and its overlying ice layers; 3) characterize the history of the surface and look for signs of recent activity.

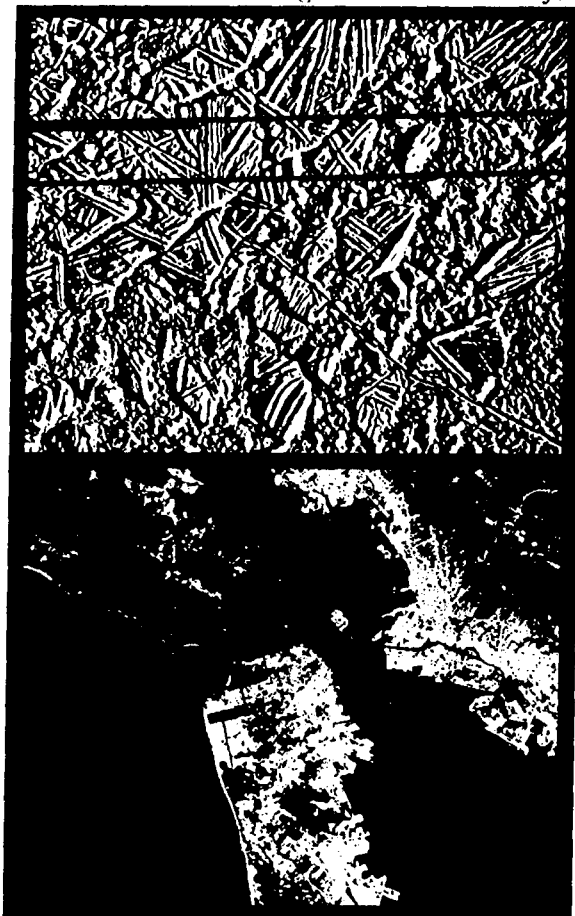


Figure 1 (top) is a *Galileo* image of "chaos terrain" showing crustal ice plates on Europa ranging up to 13 km across; (bottom) a *LandSat Thematic Mapper* image of San Francisco Bay, California to the same scale. Each image covers 34x42 km (21x26 miles) at 54 meter (59 yards) resolution.

The shape of the gravitational field of Europa and the magnitude of tidal-induced time variation in the shape of Europa can be determined by precision radio tracking of the spacecraft as it orbits in the European gravitational field, and by laser altimetry as Europa passes through apojove and perijove

in its orbit about Jupiter." An ice-penetrating radar sounder⁷ may be able to penetrate to depths of a few tens of kilometers and possibly detect an ice/liquid water or an ice/rock boundary and map the 3D distribution of the ice layer. Two imagers, a wide-angle and a narrow-angle will characterize the surface. Tentative allocations of 20 kg and 20 watts have been assigned to the science payload.

PLUTO-KUIPER EXPRESS SCIENCE

The primary science objectives for the Pluto mission are: 1) characterize the global geology and geomorphology of Pluto and Charon; 2) map the composition of the surface of Pluto and Charon; and 3) determine the composition, structure and escape rate of the neutral atmosphere of Pluto. The strawman payload consists of a visible imager to address the first objective, an infrared mapping spectrometer to address the second, and an ultraviolet spectrometer and uplink radio science experiment to address the third objective. The 7 kg mass and 6 watt power consumption of the strawman Pluto reconnaissance payload is an excellent

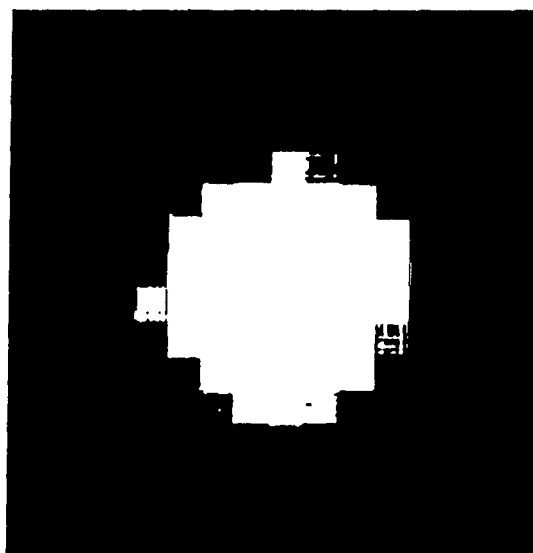


Figure 2 Pluto as seen by the Hubble Space Telescope. Courtesy A. Stern/SwRI, M. Buie/Lowell Observatory, L. Trafton/McDonald Observatory, NASA, ESA.

[i-1a1]

example of the mass and power savings possible with integrated payloads using the sciencecraft approach. This payload surpasses most of the remote sensing capabilities of Voyager 2 during its successful flyby of Triton. Breadboards of several different approaches to Pluto instrumentation were completed as part of the Pluto Advanced Technology Insertion activity.⁸

SOLAR PROBE SCIENCE

The Solar Probe mission⁹ primary science objectives are: 1) determine the mechanisms that accelerate the solar wind, 2) find the source and trace the flow of energy that heats the million-degree corona, 3) determine the three-dimensional structure of the inner corona above the polar regions and the equatorial belt, 4) map the configuration and state of the magnetic field, and the pattern of the surface and subsurface flows from pole to pole, and 5) find the origin of the fast and slow solar wind near the surface of the sun.

These objectives will be accomplished with a 16 kg, 16 watt instrument complement that is a combination of remote-sensing instruments that produce magnetograph/doppler and high spatial resolution, EUV/X-ray imaging of the solar disk, and in-situ instruments that measure

plasma distribution functions, energetic particle fluxes, magnetic field, and plasma waves. Coronal all-sky imaging will produce a 3-D tomographic map of the solar corona.

TRAJECTORY & LAUNCH OPPORTUNITIES

Europa Orbiter (EO) is to be launched on a direct trajectory in November, 2003 [(see Figure 4)]. The launch systems being considered are the Shuttle/IUS and intermediate class Evolved Expendable Launch Vehicles (EELV), both with an additional kick stage. In this scenario the flight time to Jupiter is about three years with an additional two years needed to get into Europa orbit using the Galilean satellites for gravity assist. In case EO is unable to launch in November 2003, other opportunities exist in 2004. Either of the above launch systems could be used to launch EO ~~again~~ ^{alternatively} in a direct trajectory in December 2004 and arrive at Jupiter around January 2008. ~~[Figure 5] shows~~ ^{smaller} ~~There are~~ other trajectory options using ~~current~~ launch systems like the Atlas 2AR or Delta 3, ~~The~~ ^{having} flight times to Jupiter ~~for those of~~ ^{opportunities} are 4.2 to 6.3 years.

Pluto-Kuiper Express (PKE) is to be launched in December 2004 on a Jupiter

Table 1 Ice & Fire Mission Characteristics and Launch Systems

	Europa Orbiter	Pluto Kuiper Express	Solar Probe
Trajectory Type	Direct	JGA	JGA
Launch Date	Nov 03	Dec 04	Feb 07
C3 (km ² /sec ²)	80	111 or 142	116
Flight Time (yrs)	3.2	14 or 8	3.8
Deep Space DV (m/s)	2645	300	300
Launch System	STS/ IUS or EELV	Delta 7925H or STS/IUS	Delta 3
Kick Stage	Star 48V	Star 300 or Star 48V	Star 48V

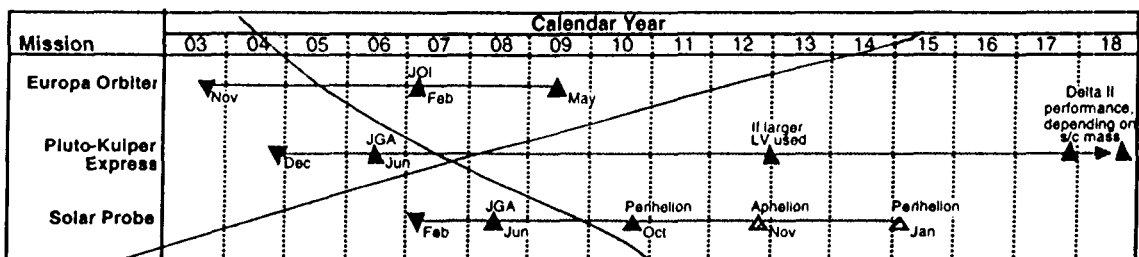


Fig 3.

extreme ultraviolet

km²/sec²

Fig 5
Gravity Assist (JGA) trajectory using a Delta 7925H/Kick Stage launch system [(Figure x)]. The flight time to Pluto could be as much as 14 years or even more depending on the launch vehicle performance and spacecraft mass. However, the flight time can be reduced to 8-9 years if PKE were to be launched on a bigger launch system like the Shuttle/IUS, Delta 3 or a medium EELV all with an additional kick stage. The launch of PKE can be moved up to November, 2003 on any of the above launch systems in case EO launch were to be delayed to 2004. After 2004, Jupiter will no longer be in position to provide a gravity assist to Pluto and resulting trajectory options are less favorable.

Fig 6
Solar Probe (SP) launch is planned on a Delta 3 class launch system with a kick stage in February, 2007 in a JGA trajectory [(see Figure x)]. This trajectory utilizes a retrograde swingby of Jupiter to cancel essentially all of the sciencecraft's heliocentric velocity, causing it to "fall" almost directly toward the Sun. This type of trajectory offers the shortest and lowest cost way to reach the Sun by using Jupiter's gravity, rather than a large propulsion subsystem, to effect the necessary maneuver. The resulting highly elliptical orbit will have perihelion close to the Sun and aphelion at more than 5 AU. The JGA targets the spacecraft for a 4 solar radii perihelion such that the direction to the Earth is perpendicular to the trajectory plane at perihelion, allowing real time telemetry during the perihelion encounter.

Fig 7
With the high gain antenna configured as the primary sun shield, this quadrature geometry, first suggested by James Randolph/JPL¹⁰, allowed the spacecraft size and mass to be significantly reduced from prior concepts having a separate shield and antenna. First perihelion for Solar Probe will occur near maximum solar activity. A second perihelion pass will be possible 4.5 years later, near solar minimum.

Table 1 summarizes the mission characteristics and primary launch systems considered for the missions. ~~It also provides~~

~~a mission timeline for the desired sequence of the Outer Planet/Solar probe missions.~~

[Images w/ credits & captions:

Jan Ludwinski

Steve

Brewster

Europa traj composites of 3 or 4 phases (Earth-Jup, long Jup orbit & initial tour, multiple resonant flybys).

Pluto JGA

SP JGA and encounter composite]

SCIENCECRAFT CONCEPTS

The general approach for the design of the Europa Orbiter, Pluto/Kuiper Express and Solar Probe sciencecraft is to have a single design team address the designs of all three sciencecraft simultaneously. Even though the launch dates are staggered, the designs will mature together. The core avionics of each sciencecraft will duplicate the X2000 avionics which are being developed currently in conjunction with the OP/SP personnel. The remainder of the sciencecraft designs will evolve concurrently and will take advantage of common components to reduce cost, schedule and risk. Currently identified common elements are shown in Table A. [***insert Karla's "Characteristic Summary" where convenient--it is 1st sheet in her Excel file. ~~Ask her for SP power level to complete the table.~~] ["TAB" OK]

Each mission is unique and the sciencecraft for each mission has specific requirements which will require incorporation of new technology to attain the science objectives. For Europa Orbiter, the radiation levels and trajectory complexity require development of systems which are very radiation tolerant, highly autonomous and very low mass. The Pluto/Kuiper Express mission requires development of very long life systems as well as high precision pointing capability driven by the low light level and fast flyby at Pluto for the infrared compositional mapping. The Solar Probe mission requires a thermal design that can withstand the intense heating produced by the extremely close

encounter with the Sun. In addition, the sciencecraft is required to go to the cold extreme at Jupiter. These hot/cold cycles require unique solutions to both thermal and power generation issues, including materials research, configuration constraints and multiple power sources. ~~A list of the currently identified technologies is shown in Table B.~~

For both Europa Orbiter and Pluto-Kuiper Express, the lack of solar energy at the target body distances appear to require that radioisotope power systems be used. While still ongoing, alternative power studies to date have produced no credible solution to achieving mission science objectives with solar power. A two-phased development to reduce the amount of radioisotope needed to meet the needs of these missions is underway. The first phase is to incorporate low power electronic design to reduce the power demand by the sciencecraft. The second phase is to increase the thermal-to-electric conversion efficiency such that a smaller amount of radioisotope fuel suffices to produce the same electrical power.

Europa Orbiter

The current design for the Europa Orbiter is shown in Figure [XX]. For the Europa mission, the electronics, largely consisting of the X2000 First Delivery avionics ^{package} ~~bus~~, will be integrated onto Integrated Avionics Structure (IAS) panels and then interfaced with a 700 kg wet mass dual mode bipropellant propulsion module and a high gain antenna. Power is supplied for the sciencecraft via the ARPS, which can deliver 150 W during Europa orbit, and

supplemented by a battery for peak power demands.

Because spacecraft lifetime in orbit at Europa is severely constrained by the radiation environment (2 Mrad/month behind 100 mils of Al), a high data rate downlink is needed to return all of the science data desired within the expected lifetime of the mission. Currently, an X-band telecommunications subsystem is baselined, though Ka-Band alternatives will be investigated over the next year.

The mass of the sciencecraft, which is limited by the lift capability of the launch vehicle, is a significant issue which is continually being addressed through trade studies and design decisions. The mass is driven mainly by the amount of propellant required for the mission's many maneuvers culminating in Europa orbit insertion and the severe radiation environment. Configurational studies are constantly being performed to take advantage of the inherent shielding provided by the sciencecraft to reduce the added radiation shielding mass.

Pluto-Kuiper Express

The Pluto-Kuiper Express sciencecraft is depicted in Figure [XX]. For Pluto/Kuiper Express, the same core set of electronics which is flown on Europa Orbiter will be mated with a 65 kg wet mass hydrazine monopropellant propulsion module. In the current concept, power is supplied by the ARPS, which can deliver 130 W at Pluto encounter. A battery may also be included to handle short term power requirements during encounter.

[incorporate any comments from Ann - here or elsewhere in doc.]

Fig 8

Fig 9

[Steve - here's the rest that I
hadn't marked up before. This
9/6/3/10 PM 201]

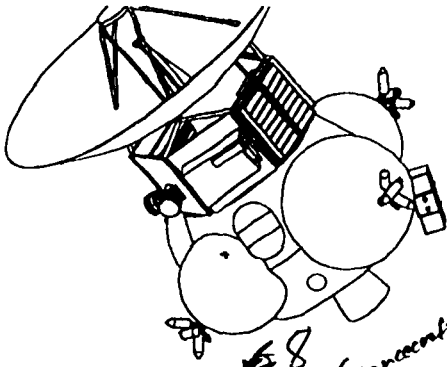


Fig 8
Europa Sciencecraft
figure to be embedded in

To reduce costs, it is envisioned that the same X-band telecommunications system will be used for Pluto-Kuiper Express as flown on Europa Orbiter.

Solar Probe

The Solar Probe sciencecraft is shown in Figure [XX]. The integral heat shield and high-gain antenna is sized to keep the rest of the flight system in its shadow or umbra at perihelion 3 solar radii from the Sun's photosphere. The avionics will operate at room temperature. High temperature carbon-carbon materials have been tested for the shield, assuring that the mass loss rate is sufficiently low to avoid interference with the plasma science measurements.¹¹

A diverse set of power sources, including solar arrays and batteries, are required to survive the extremes in insolation between the dim cold of the near-Jupiter range and the extreme heat of a close encounter of the Sun. In the present concept, the sciencecraft utilizes low intensity solar arrays from Earth out to Jupiter, and back to about 0.5 AU from the Sun. These arrays may utilize the same cell and deployment technology under consideration for the DS4/Champion mission. Because the sciencecraft is not required to perform science observations or critical maneuvers during the Jupiter flyby, the modest 60W power produced is sufficient, with battery

augmentation for peak loads. At about 0.5 AU, the low intensity arrays are jettisoned, and small high temperature arrays are deployed for use in to ~0.1 AU or closer. When the solar flux is too high, these arrays are retracted under the shield's umbra, and re-deployed after perihelion. Solar Probe uses battery power during the perihelion pass. To enable the second perihelion, the present concept is to essentially put the sciencecraft to sleep, while using radioisotope heater units (RHUs) to keep propellant, valves and electronics warm enough to avoid freezing during the 4.5 year round trip to ~5 AU solar distance and back toward the Sun.

The avionics design will be identical to that of Europa Orbiter and Pluto/Kuiper Express. Due to the unique shield geometry and thermal requirements, the configuration of the avionics and propulsion components will be significantly different from either of the other two sciencecraft, though some propulsion components are likely to be common.

Advanced Radioisotope Power Source (ARPS)

The new power source being developed by X2000 and the Department of Energy for possible use on the Europa Orbiter, Pluto-Kuiper Express and other future missions is based upon the general purpose heat source (GPMS) modules used previously on the *Galileo*, *Ulysses* and *Cassini* spacecraft. ~~***see if you can get a biblio reference from Jack Mondt~~ These "bricks" provide the

[already referenced, #?]

thermal energy which is converted to electrical power by means of a sodium heat pipe system known as Alkalai Metal Thermal to Electric Converter (AMTEC). This new conversion technology promises up to 20% conversion efficiency, with 11% shown on current test cells. The conversion efficiency of the *Cassini* type Radioisotope Thermoelectric Converters (RTGs) was ~6%.

This efficiency improvement, along with low power consumption electronics, allows the total amount of radioisotope flown to be reduced to ~1/14 the mass of that flown on *Cassini*.

[0.5pg figure showing all three, or one each
Karla/Steve]

OPERATIONS CONCEPTS

Operations costs for all three Ice & Fire missions will be minimized by sharing a single core flight team and a common ground data system. This approach is enabled by the common avionics design shared by all three sciencecraft together with a large percentage of common flight software. Each mission will supplement the shared ops capability with a few mission-dedicated personnel including, mission planners, instrument reps, and science investigation teams. Operations experience, software tools, and lessons learned on the first mission will help to reduce costs for all three missions.

The ability to operate two sciencecraft at a time will be provided by a second OP/SP Project Operations Center (POC) located at a selected university. A workstation-based ground data system design makes implementation of this replica POC at a university cost effective. Sharing flight operations with a team of university students and professionals allows cost effective use of a very small team of JPL experts who will delegate routine operations tasks to the university team. The university team will also represent a cost effective resource for developing prototype continuous improvement software, for new operator training, and as a source of experienced

spacecraft operators; an important need for the long duration of OP/SP mission operations.

Several new technology developments have been identified to reduce operations costs. A radio "beacon" tone signaling system will allow the ground to check on sciencecraft status using a more cost effective simplified verification scheme. The sciencecraft on-board memories, sized to accommodate storage of encounter science data, will be used as an on-board engineering data archive during cruise. Sciencecraft performance analysis will be performed on-board using this data. Only engineering summary data or data associated with anomalies requiring ground analysis will get downlinked. A command and sequencing capability that accommodates event-driven commands and permits adaptive, closed loop control will replace the more expensive, traditional ground process of developing model-based, constraint checked, zero-defect, simulated timed-command sequences.

Possibilities also exist for employing onboard algorithms for science data processing with the goal of utilizing intermediate analysis results to prioritize downlink. Such a capability could be used to expedite post-encounter data playback on Pluto-Kuiper Express for example, or to flag images where change has been detected on the European surface, possibly due to ice crust tectonics, by comparing new images to archived images onboard.

RISK MANAGEMENT

The purpose of risk management is to provide a ~~mechanism~~, or process, for predicting possible breakdowns and managing them within the cost, schedule and technical constraints of the project. The OP/SP project will have a process that identifies risks early, generates mitigation strategies and determines financial and schedule the impact on the mission.

The process involves the submission of significant risk lists (SRL's) from the project element managers (PEM's) to the risk

manager. These lists contain an explanation of the risk event, the likelihood of occurrence and the consequences of the risk occurrence. "Risk" is defined as the product of the likelihood and the consequence.

Risk management is performed throughout the Project life cycle. SRL's are submitted as appropriate and reviewed periodically. The SRL data base is dynamic in that some risks are retired as the Program progresses, as other risks are added.

[**pls add titles to this matrix for Likelihood, Consequences, and Risk, from Rich K.]

Likelihood	H	L	M	H	M
	M	L	M	M	H
	L	L	L	M	M
	N	N	L	L	M
		N	L	M	H

Consequence

The above table shows a qualitative rating of the likelihood vs. consequences where:

N = negligible

L = low

M = moderate

H = high

for "likelihood" and "consequences" often
These qualitative values can be substituted for actual values based upon analyses and/or engineering judgement.

For a given risk event, the project manager, with assistance from the PEM's, risk manager and others, will determine the cost and schedule impacts for doing nothing and for the implementation of the risk mitigating options. Analyses of when the risk event will occur and when the mitigation option decisions must be made, along with the decision criteria for the selection of the various mitigating options, will be performed. Ideally, this will enable the project to proactively plan for breakdowns, generate mitigating options and effectively manage resources, and hence, successfully manage the Project's risks. based on a project-wide understanding and prioritization of risks.

Primary types of risk inherent in the OP/SP project include many in common with other

projects. A few unusual aspects of the OP/SP missions are noted below, along with the general approach to address these risks.

1. Each mission depends on a set of new, as-yet unproven technologies. The missions depend on several other programs for technology development. *The X2000 First Delivery and ARPS activities, which are the source of most of the new technologies, were funded beginning in FY98, and have substantial resources through 2002 to apply to the OP/SP technology challenges. Shared staff, engineering databases, and meeting attendance between these activities facilitates rapid and accurate communication and early detection and resolution of problems. Other technologies are being demonstrated on the New Millennium Deep Space 1 mission, planned for launch this summer, so there is significant lead time for nearly every technology and some time remains to pursue alternates if that is required. Nearly every new technology required has an alternate which requires some combination of greater mass, power, cost, and/or sacrifice in performance. The possibility of needing to switch to any small number of alternates will be accounted for in cost, schedule, mass, power and performance reserves.*

2. The Europa Orbiter mission is the most technically challenging, yet is the first mission in the sequence. This mission can be delayed 13 months, with the less-challenging Pluto-Kuiper Express launched in its place. Development between now and 2000 will proceed in parallel for the two missions toward the 2003 November launch readiness date. A switch of the mission order could be accomplished within planned resources before passing. "technology gates" now being established; a later switch would be more costly, but many of the critical X2000 tests, including many associated with radiation (see Fig. 11)***Rich's dose curves for the missions, will be completed before these "gates." Europa Orbiter is being used as the primary requirements driver for most X2000 technology developments.

3. Pluto-Kuiper Express is a very long mission. The environment on the way to Pluto, with the possible exception of the

Fig 11

Jupiter flyby, is very benign, and successful long duration interplanetary missions, as well as Earth orbiters, are now common. Special attention is being given to possible ARPS degradation mechanisms and accelerated life testing.

4. Solar Probe encounters the Sun for the first time near solar maximum, when coronal mass ejections (i.e., flares) raise the probability of a fatal dose of energetic protons. Preliminary analyses¹² indicate that the probability of a fatal dose during the first perihelion is ~~much less than the probability of launch vehicle failure~~. While undesirable, this is an acceptable risk.

5. By performing the three missions as part of a single project, there is a risk that problems with the early missions will jeopardize adequate resources for later missions. After preliminary design, each mission will be individually cost capped, with a descope plan to relieve potential cost and/or schedule overruns. Margins and reserves will be carried for each mission, and a single mission manager will be held accountable for within-cost, on-time success. If the missions were performed as separate projects, there would still be risk of overruns. Within the same project, this risk still exists, but the same resources can be more effectively utilized to address similar risks among all three missions.

[Radiation environments graph for all 3 and explanatory caption.

Brewster]

Steve

ADDITIONAL APPROACHES TO MINIMIZE COST

Science & Instruments

The most significant departure from previous practice will be the early incorporation of science teams into the flight project team. The intent of this is to allow participation of the science team in the early

design and development of the flight system, to design a "sciencecraft" around the mission's critical measurements, rather than a "spacecraft," with "payload" added later.¹³ This is intended to help avoid costly late modifications to the flight system and promote the smooth integration of science into the flight system. Where appropriate, the competitive mission science selection process will solicit complete, integrated, conflict-free science investigations under a single Principal Investigator that fulfill most or all the science objectives of a mission. This will mitigate the costs associated with conflicts between experiments and instruments in resource requirements and flight operations. In addition, this will promote the sharing between instruments of subsystems such as foreoptics, electronics, and software, thereby reducing duplication.

Launch systems & launch site ops^{eration}

Current and future NASA planetary missions cannot afford to select the most capable and largest launch systems due to the huge costs to procure them. In a full-cost accounting approach for a mission, even a modest launch system can account for close to half of total mission cost. Therefore, it becomes imperative to minimize the spacecraft mass and choose trajectory options such that low cost launch systems can be used to fit within the overall budgetary constraints for the missions. The availability of a low cost (to the Project) Shuttle/surplus IUS system or the projected low cost intermediate class Evolved Expendable Launch Vehicle (EELV) in the future opens up the possibility of using the desired direct trajectory for the heavier Europa Orbiter mission. For Pluto-Kuiper ~~mission~~ ^{Express} the present plan is to use a Delta 7925H/ Star 30C launch vehicle to minimize cost while accepting a longer flight time, and increased operational cost. If a second Shuttle/surplus IUS is available after Europa, cost to the project is similar, flight time is reduced to 8-9 years, and a large mass margin would allow addition of a technology demonstration such as a Jupiter Deep Probe or Pluto Microlander. (Any such added payload would require funding outside the OP/SP project, perhaps in an

arrangement like the one used to fly the New Millennium Deep Space 2 Microprobes on the Mars Surveyor '98 Lander mission.) From a cost standpoint, the next best option for Pluto would be to use a Delta 3/ Star 48V system which is already planned for the Solar Probe mission. Apart from the substantial reduction in Pluto flight time (and cost) from ~14 years to 8-9 year, this dual use of the Delta 3 would allow for cost reduction through synergy and commonality of hardware, software and launch system integration for both the missions. A life cycle cost comparison of the Delta 2, Delta 3 and Shuttle options is in progress.

Kennedy Space Center

At an institutional level, JPL and KSC *personnel* jointly ~~are~~ exploring and assessing ways to reduce the launch operations time at the Cape. The stretch goal is to reduce the time from shipment of the spacecraft to the Cape ~~to and its subsequent~~ launch to less than 30 days from the current time of about four months on expendable launch systems. This is bound to have significant beneficial cost impact on the missions in the future. Launch on the Shuttle, however, ~~has to go~~ *presently* through ~~the customary~~ *more* complex operational requirements verification and procedures ~~to be accepted for launch~~. This process could take as much as twenty weeks at the Cape-eight for the spacecraft assembly and test, six at the Shuttle Vertical Processing Facility for integration, and six at the launch pad before being ready for launch.

~~Approaches to minimize cost -~~ Trajectory/Mission Design/Navigation

To minimize costs in the mission design/navigation area for the OP/SP missions, we are investing in new automated navigation capabilities for both ground and on-board operations. This is especially true for Europa Orbiter. *Galileo* was required to constrain its tour of Jupiter's system such that the minimum time between satellite encounters was at least 25 days, and perhaps more importantly, such that major deterministic trajectory events were separated by at least two weeks. To keep the very high mission ΔV requirement manageable, Europa Orbiter will have to accommodate large

maneuvers (up to 100 m/s) within days of other maneuvers and/or satellite flybys. Such demands will require orbit determination and maneuver optimization/design to be performed on a very short schedule. Automation of this process promises to greatly reduce the cost, in both time and money, for the implementation of this challenging mission/navigation design. It has been estimated that such capability, when combined with the tight design focus discussed in the following paragraph, would have saved *Galileo* 16 work years in maneuver analysis alone over its 8 year mission¹⁴. These new capabilities, where appropriate, will be applied to Pluto-Kuiper Express and Solar Probe to realize cost savings.

Other cost saving approaches are being incorporated into the mission design/navigation area. For Europa Orbiter, these include maintaining a tight focus on getting into Europa orbit as quickly as possible while minimizing ΔV and radiation exposure (extensive mission design resources were spent on optimizing the *Galileo* tour for science opportunities), and postponing much of the final trajectory and encounter design until after launch to minimize work that is subject to change as a result of the actual launch date. For all OP/SP missions, involvement of university partners¹⁵ in trajectory design work, maintenance of adequate ΔV margin, and early software tool investment will contribute to our ability to perform the challenging missions within cost.

Flight Systems

Though the three sciencecraft will be launched over a period of 3-4 years, the initial design will be performed by the same personnel assigned to a joint design team. This team will continue into the detailed design of the Europa Orbiter and Pluto-Kuiper Express sciencecraft while identifying

¹⁴ We have an ongoing relationship with the School of Aeronautics and Astronautics at Purdue University that has resulted in several valuable trajectory opportunity surveys for both the Europa Orbiter and Pluto-Kuiper Express missions.

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endnotes*

areas of commonality for incorporation later into the detailed design of the Solar Probe sciencecraft. Common subsystem designs will be used wherever possible to minimize the cost of developing and testing each sciencecraft.

In addition, the software architecture is designed such that a core set of software functions are coded and used for each mission. Some mission specific software will be required for each mission to specifically address those very unique aspects of the mission. This core architecture will not only allow for the reduced cost in the development and testing of the software but will allow for smaller flight operations teams to monitor and operate the sciencecraft in flight.

A common hardware approach and software approach will minimize the development effort on the ground and will allow multiple sciencecraft to be simulated on a single testbed with common procedures and processes. Also, this allows for commonality in sparing of the hardware which decreases the recurring hardware expenses.

avionics, software, and other equipment
The X2000 First Delivery is planned as a multimission ~~bus~~ ^{have} for the Europa and Pluto missions, and the recurring cost for ~~a flight~~ ^{the} ~~qualified bus~~ ^{equipment} is expected to be very low. The propulsion modules and science packages are unique; however, ~~and they will be more of a factor in the total cost of those missions.~~ These mission-unique costs are borne by each individual mission, but by using a common ^{flight} ~~bus~~ ^{and} support ~~equipment~~ ^{test} equipment, and common ground and flight software modules, each mission can reduce its integration and test costs.

Other technologies incorporated into the designs of the sciencecraft which are required for mission success. Whenever possible, leveraging of technology developments supported by other JPL missions and/or technology development programs has been used ^{where other work} ~~if the needs match~~ ^{arrangement} with the needs of OP/SP. Such ~~cooperations~~ ^{close enough} include incorporation of technologies also supported by New Millennium Program and the Mars Program. Some mission unique

^{e.g.,} technology (heat shield/antenna for Solar Probe) requires that OP/SP support the development, ~~wholly on its own.~~ (See Table B)

[***insert Karla's "Technology" Summary" table, from my corrected file "Karla's IAA.tab," where convenient.]

OPPORTUNITIES FOR INVOLVEMENT

Industry will play a major role in the OP/SP missions, in addition to being the source of most of the components and subsystems for each sciencecraft. It is presently expected that the Europa Orbiter sciencecraft, with its unprecedented challenges from the radiation environment, will be integrated at JPL. A solicitation is planned whereby an industry collaborator will be selected to work on this flight system, followed by integration of the Pluto-Kuiper Express and Solar Probe flight systems at the collaborator's facility, based on the avionics, software, and much of the other equipment first used for Europa Orbiter.

*Rob verify
OK w/ G
to say
4/27 only*

The science community is to be involved through the competitive NASA Announcement of Opportunity selection process. Europa, Pluto, and Solar Probe Science Definition Teams are now preparing advice for NASA on how such solicitations may be structured to get the best science capabilities for minimum cost.

Over 100 university students have been involved since the inception of the original small Pluto mission proposal, performing engineering, artistic & graphics design, office and educational outreach tasks, with some students receiving college credit and others pay for their work. [***pls put in alpha order, OK to group similar names as done here] Art Center College of Design, Caltech, Harvey Mudd College, the Universities of California, Colorado, Michigan, Naples (Italy), ~~and Washington,~~ Central State, Purdue, Southampton (UK), and Tuskegee Universities, the U.S. Air Force Academy, Naval Postgraduate School, Technical University of Munich, International Space University, and Georgia Tech are some of the schools whose students

have worked on one or more of the OP/SP missions.

As with many other missions, NASA may consider opportunities for involvement of other space agencies.

CONCLUSIONS

At the beginning of this decade, ~~studies of~~ ^{concepts for} ~~earlier~~ Pluto and Solar Probe mission concepts, ^{very} ~~placed them~~ in the *Voyager/Galileo/Cassini* size and cost class.¹⁵ With that kind of dry sciencecraft mass, no single available launch vehicle could have launched a Europa Orbiter toward Jupiter. Since then, major changes in the Solar System Exploration and Sun-Earth Connection disciplines make these three missions credible at a fraction of earlier costs.

The first change, which drove the whole community, was that high-cost missions once or twice a decade simply became unsupportable with changing priorities of the country. In response to this, the science community became willing to make more modest demands on individual mission science capabilities; only the highest priority science objectives were allowed to drive designs, especially in an era where different Solar System science missions are now launching more than once a year. Also, engineers, scientists, and industry and Government laboratory management communities have simply gotten smarter about how to design, develop and implement missions more cheaply, enabled in part by the experience of the very challenging missions which came first. *Mars Pathfinder* and *Near Earth Asteroid Rendezvous*, the first two Discovery missions, are some of the best examples that set new benchmarks. Technologies have improved dramatically, driven especially by developments in the electronics industry, and the availability of once-classified technologies that have formed the basis for new, lightweight, low power instruments, electronics, antennas, and other equipment. Software which can be developed, tested and flown on common computers can reduce development,

integration, test and operations costs by serving the entire lifecycle, and by allowing equipment in flight to be reprogrammed more easily to serve new functions and to re-use software across missions.

Interdependence is perhaps the next major change which will reduce mission costs, at some risk of common flaws affecting several missions. The OP/SP missions depend critically on technologies being developed as part of X2000 for a variety of customers, as well as developments from the New Millennium, Mars, and cross-enterprise NASA programs. There are also a variety of technology development partners from industry, academia, and other Government agencies who are working with the various programs on which OP/SP depends, in many cases applying their own funding and getting benefits for their unique missions. Conversely, many developments initiated for the Pluto mission have found their way into New Millennium, X2000 and other programs. Later missions are likely to be planned based on inheriting technologies first developed for the OP/SP missions.

These missions to the ends of the Solar System, and to Europa in the middle, represent important steps in NASA's Space Science Strategic Plan.¹⁶ They will only be achievable within projected costs within an interdependent, mutually supportive environment of science communities, technology developers and mission implementers. The best ideas are welcome for how to best achieve this.

ACKNOWLEDGMENTS

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The authors wish to thank Linda Liveness for her able assistance.

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[Figures & Tables follow:

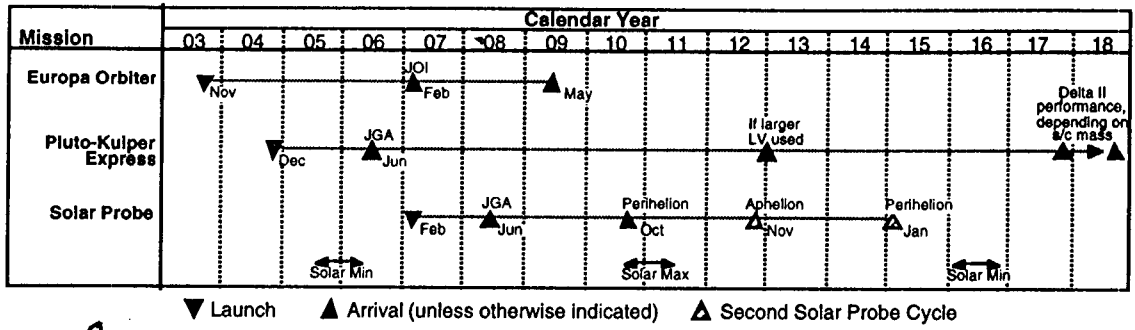
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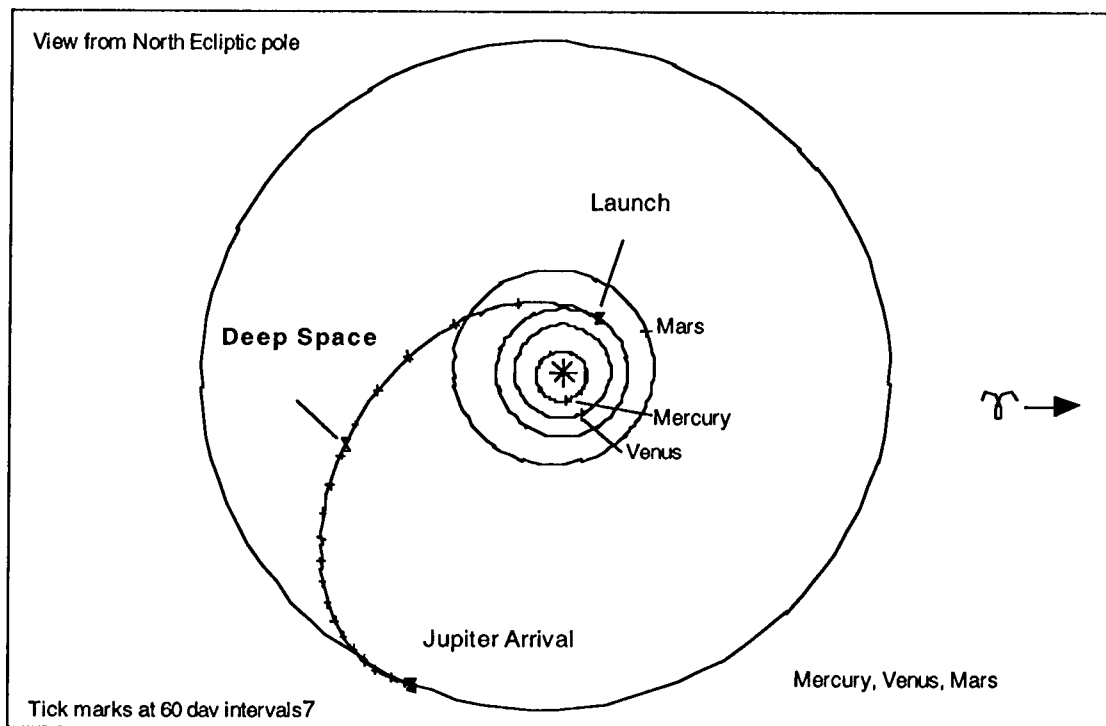
Fig 3

Figure X Solar Eclipse image [Brad Provin??]; Solar soft x-ray image SOHO; Solar Probe spacecraft

From Jan Ludwinski:



⁰
Figure 3 Outer Planets/Solar Probe multimission timeline.

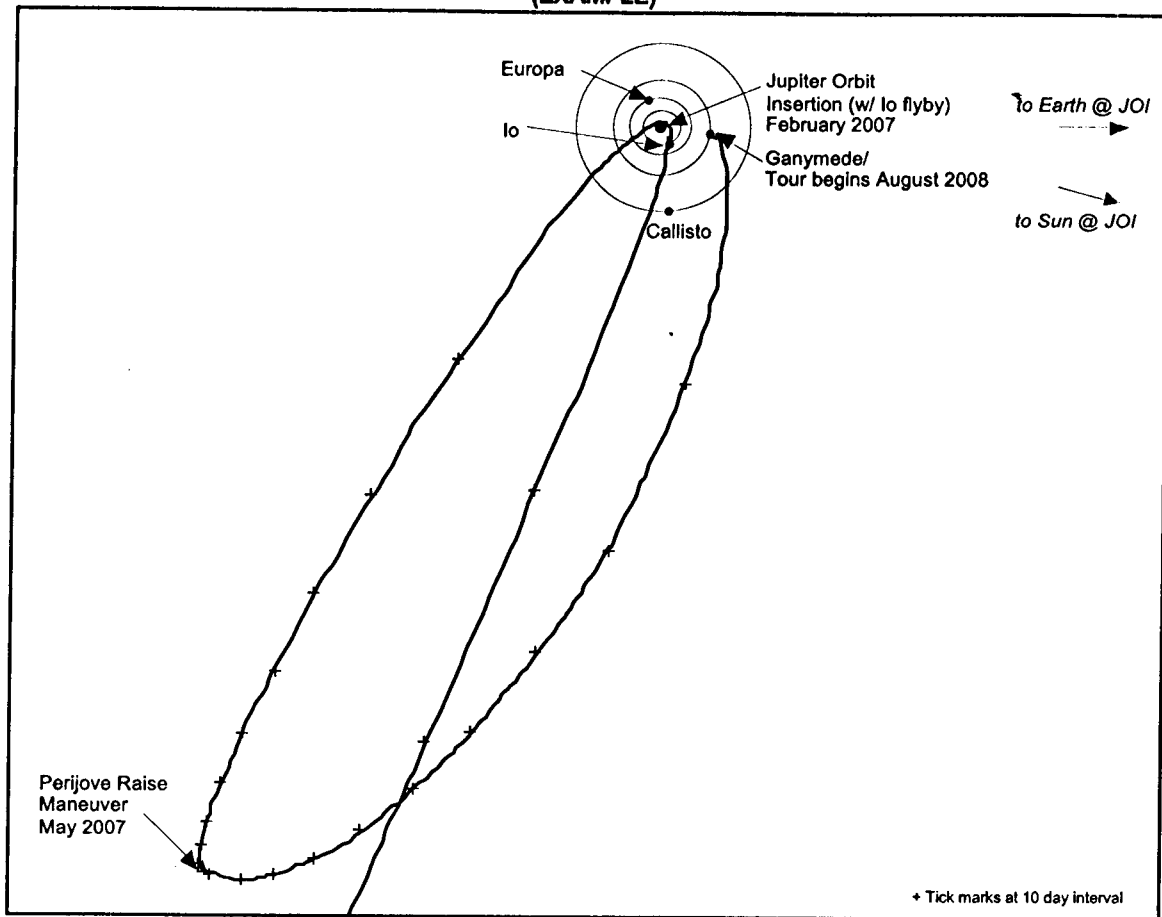


^{4a}
Figure 4 Europa Orbiter: 2003 launch, direct trajectory: ⁶ Jupiter.

Fig 4b,

Jupiter

-2003 Europa Orbiter - Initial Orbit Trajectory (example).
(EXAMPLE)

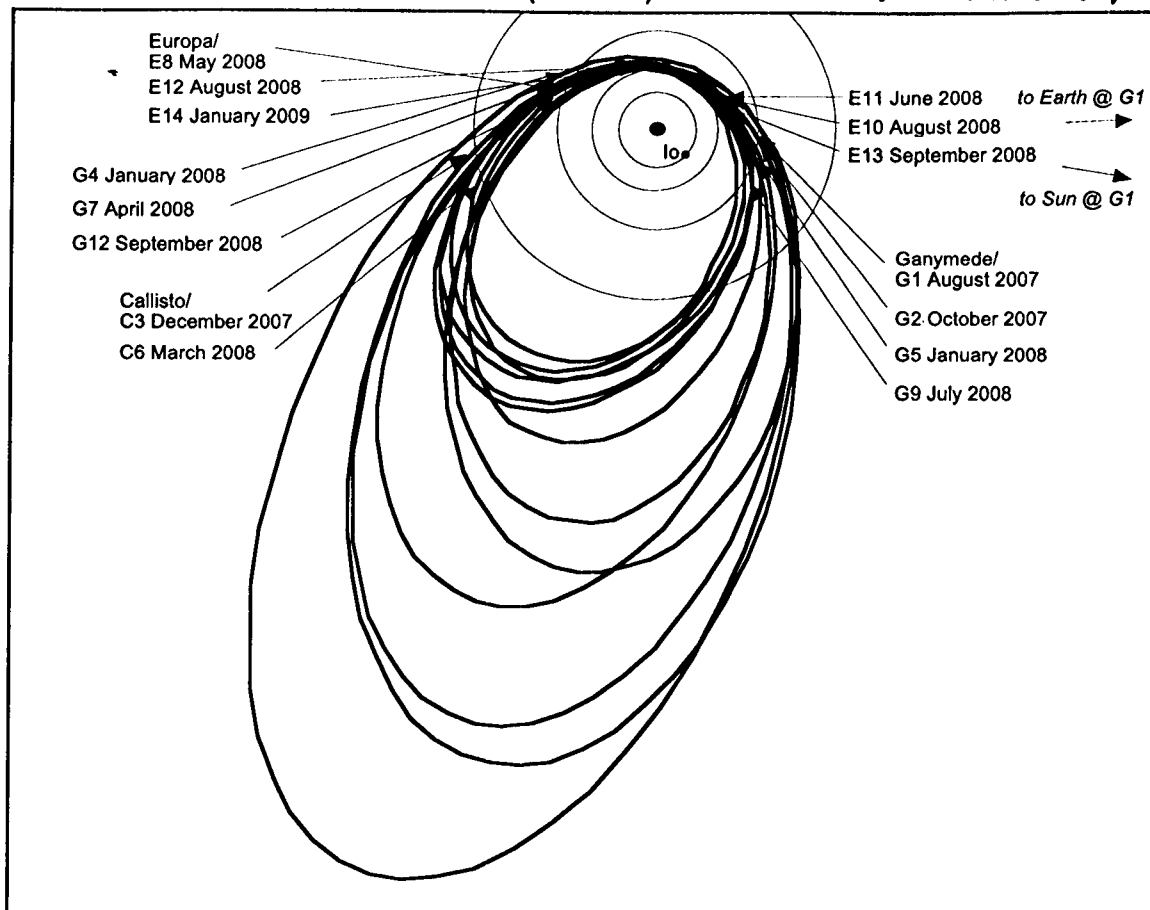


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Fig 4c

2003 Europa Orbiter - "Galileo" Tour Trajectory
(EXAMPLE)

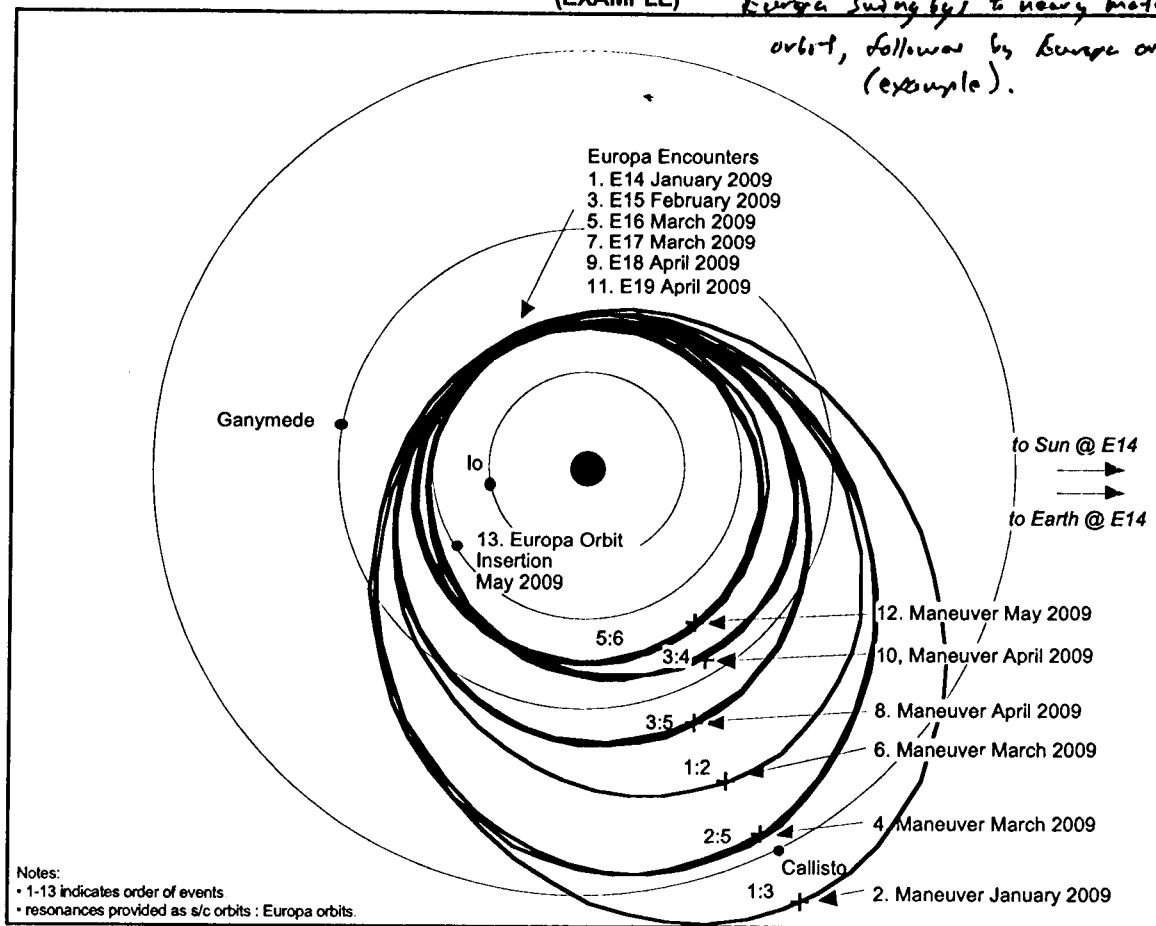
like multi-satellite "Tour" trajectories used to pump down the size of the orbit around Jupiter



RWM 3/5/98

Fig 4d1

2003 Europa Orbiter - "Endgame" Trajectory phase using multiple resonant
(EXAMPLE) Europa swing bys to nearly match Europa's
orbit, followed by Europa orbit insertion
(example).



RWM 3/5/98

Fig 5

2004 Pluto-Kuiper Express - Jupiter Gravity Assist Trajectory
(EXAMPLE)

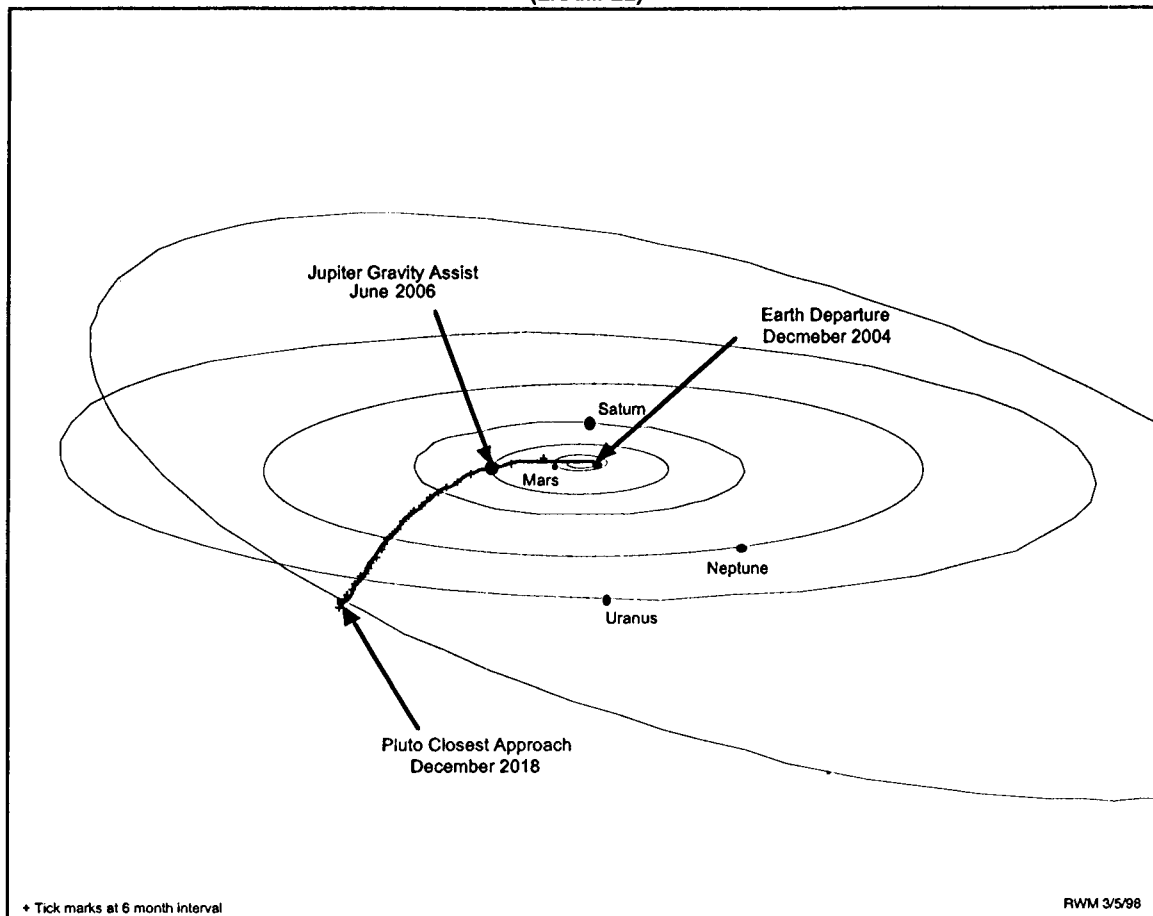


Fig 6

2007 Solar Probe - Jupiter Gravity Assist Trajectory
(EXAMPLE)

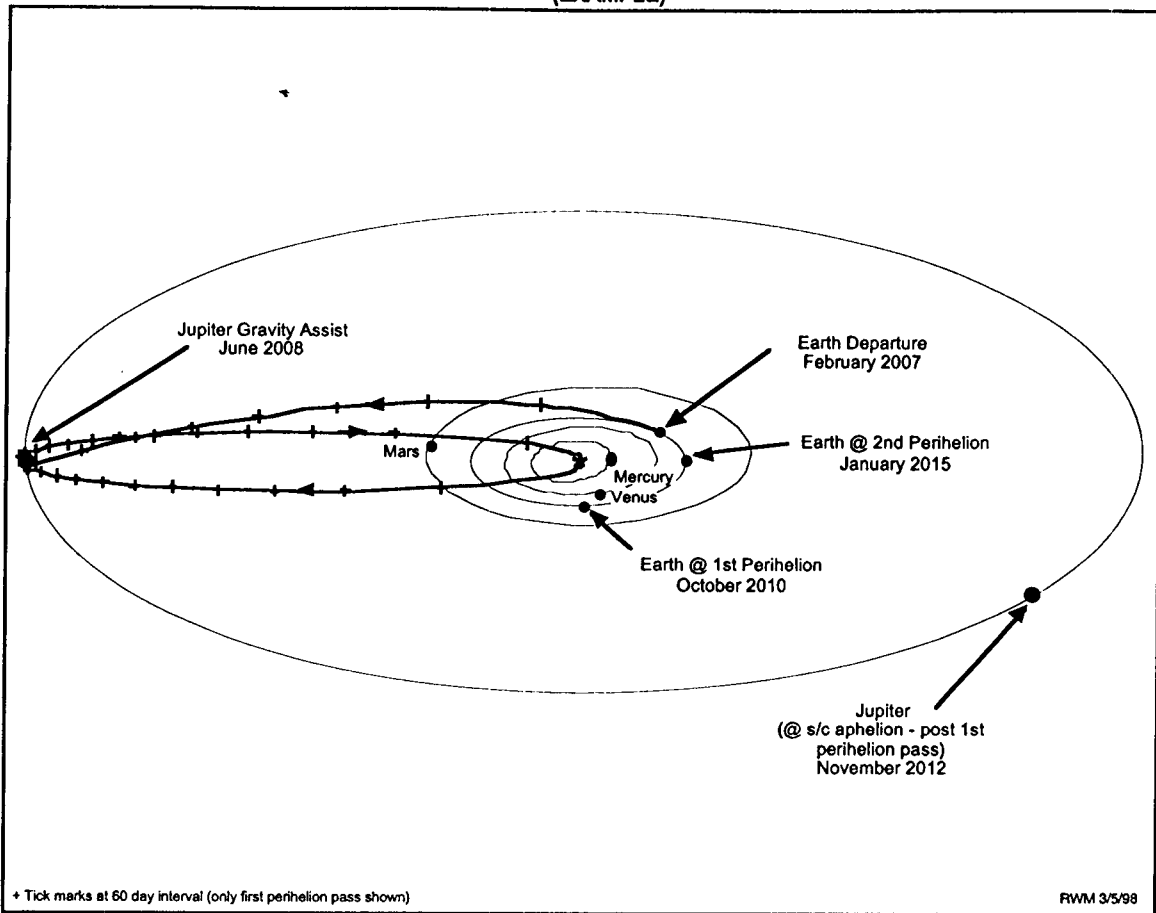


Fig 7 Solar Probe near-perihelion trajectory.

[Steve - This part the sun.
• Steve's shared stuff]

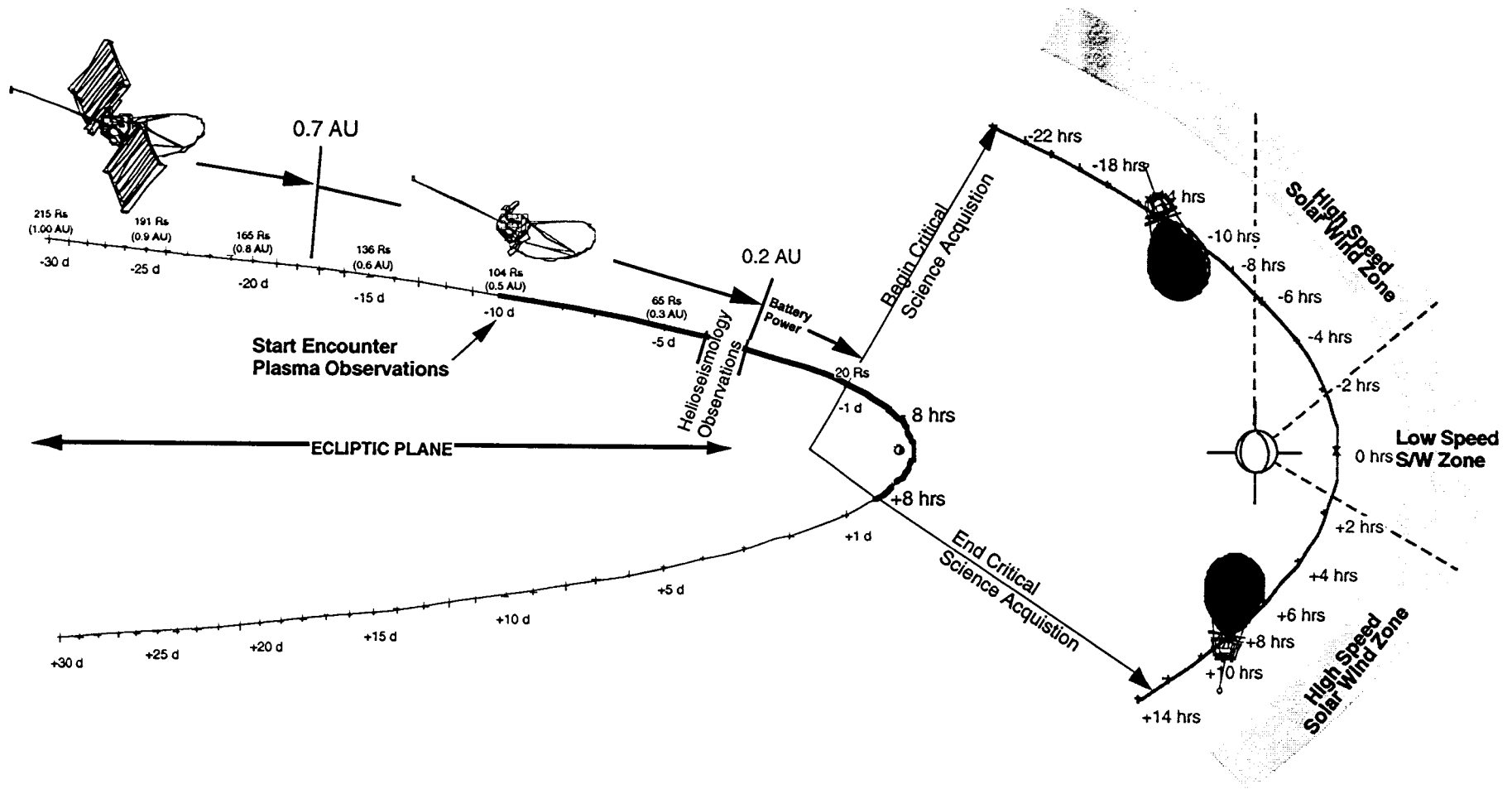


Table A: ~~Scholarcraft~~ Characteristic Summary

Characteristic	Unit	Europa Orbiter	Pluto-Kuiper Express	Solar Probe
Lifetime	years	8.5 years	14	9
Power at Primary Mission	Watts	150 W	130	TBD
Power Source		ARPS, Secondary Battery	ARPS, Secondary Battery	Solar Arrays, Secondary Battery
Telecom Subsystem		X-Band RF	X-Band RF	X-Band RF
Radiation Level	krad	25000		
(Behind 100 mils Al)	krad	4000	80	80
Electronics Requirement	krad	1000	200	200
Propulsion Subsystem		Bi propellant	Mono propellant	Mono propellant
Delta V Capability	m/s	~2700	300	300
Pointing Capability	mR	2	2	2

Pluto-Kuiper Express

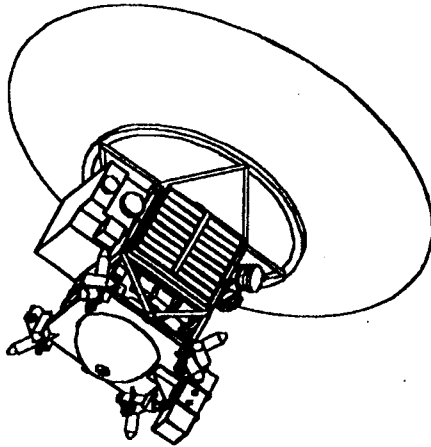


Fig 9

For Pluto/Kuiper Express, the same core set of electronics which is flown on Europa Orbiter will be mated with a 65 kg wet mass hydrazine monopropellant propulsion module. In the current concept, power is supplied by the ARPS, which can deliver 130 W at Pluto encounter. A battery may also be included to handle short term power requirements during encounter.

To reduce costs, it is envisioned that the same X-band telecommunications system will be used for Pluto-Kuiper Express as flown on Europa Orbiter.

Solar Probe

The Solar Probe sciencecraft is shown in Figure [x]. The integral heat shield and high-gain antenna is sized to keep the rest of the flight system in its shadow or umbra at perihelion 3 solar radii from the Sun's photosphere. The avionics will operate at room temperature. High temperature carbon-carbon materials have been tested for the shield, assuring that the mass loss rate is sufficiently low to avoid interference with the plasma science measurements.¹¹

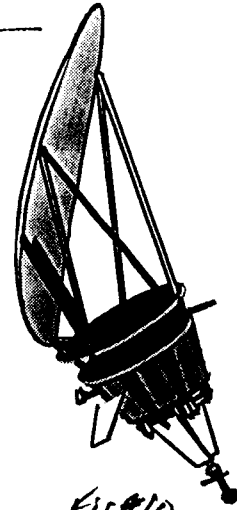
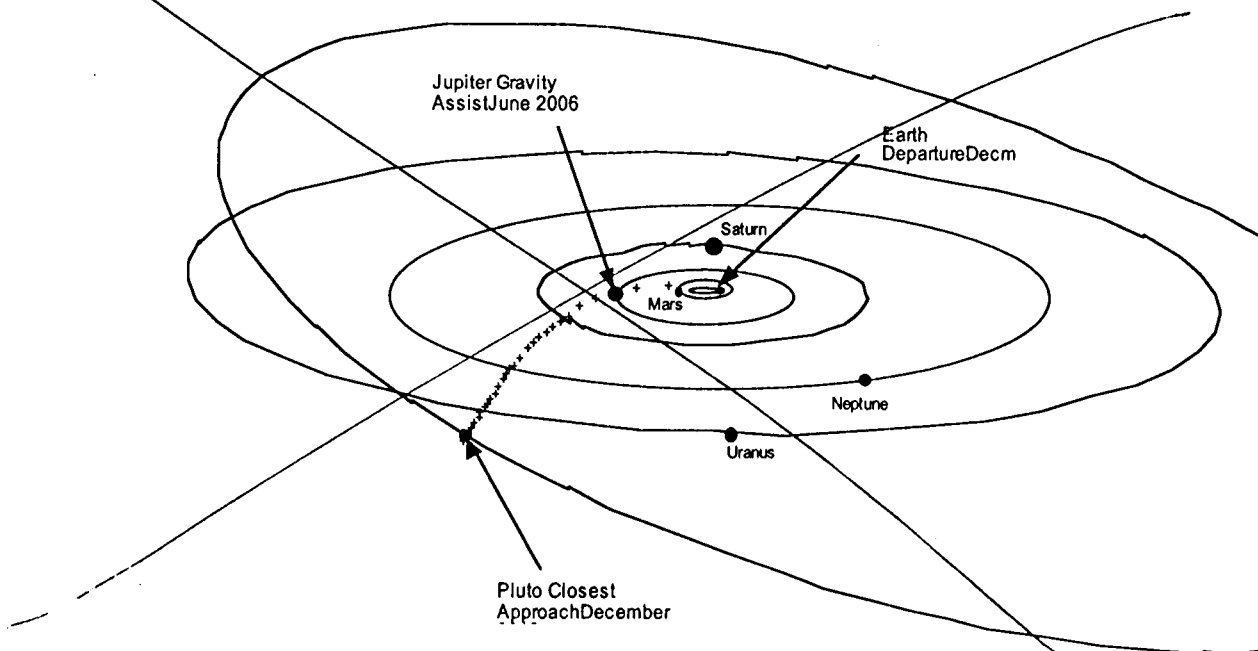


Fig 10

A diverse set of power sources, including solar arrays and batteries, are required to survive the extremes in insolation between the dim cold of the near Jupiter range and the extreme heat of a close encounter of the Sun. In the present concept, the sciencecraft utilizes low intensity solar arrays from Earth out to Jupiter, and back to about 0.5 AU from the Sun. These arrays may utilize

Fig 8 → [+ similar figure for Europa Sciencecraft]



From Rich Kemski:

Dose vs. Depth Curves (4 pi Spherical Shell)

ROM = 1

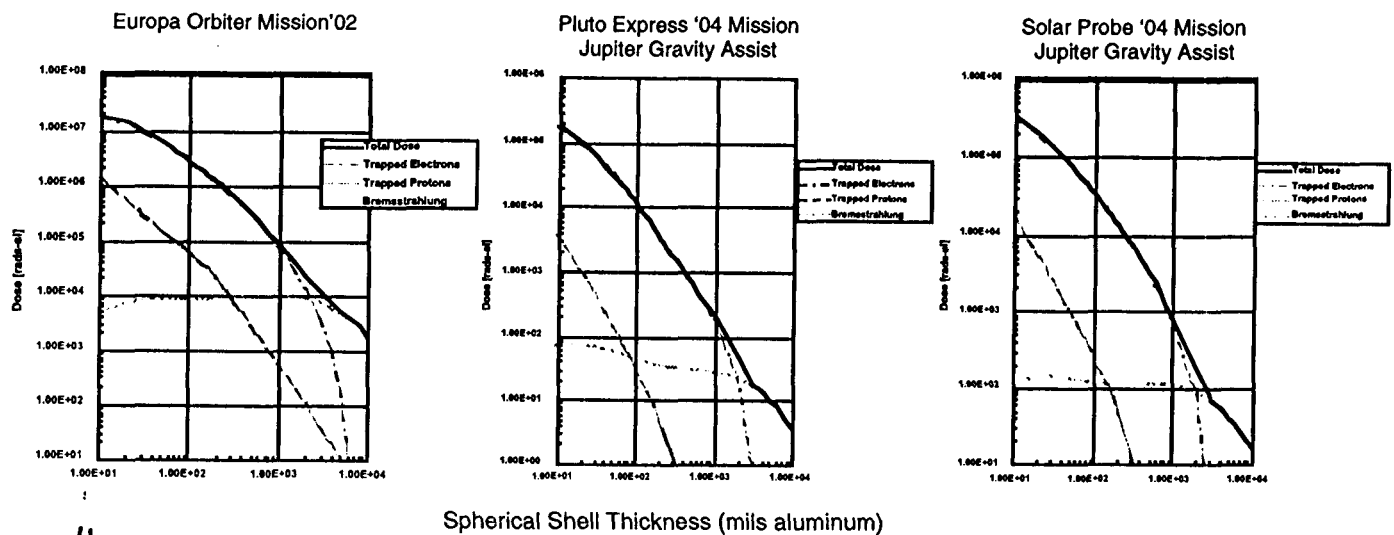


Figure 4 Dose versus depth curves for Outer Planets/Solar Probe missions. Note that these curves we derived for different mission dates than currently planned. Little difference is expected for the currently-planned mission dates, however, to within the accuracy of the radiation models.

Table B : Technology Summary

Technology Item	Sources
Propulsion Technology	X2000, Industry
Shield Technology	OP/SP
Solar Arrays/Batteries	OP/SP, Mars, NMP
High Efficiency/low mass RF telecom	Mars, TMOD
Radioisotope Power Source	X2000/DOE
Radiation Hard Electronics/Sensors	X2000, Mars, OP/SP
Spacecraft Autonomy Software	NMP, X2000, Industry
Advanced Instrument Technology	OP/SP, Mars
Microelectronics Technology	X2000

OP/SP = Outer Planets/Solar Probe Project

Mars = Mars Program

TMOD = Telecommunications and Mission Operations Directorate, JPL

NMP = New Millenium Program